Comparison of the Total Charged-Particle Multiplicity in High-Energy Heavy Ion Collisions with e^+e^- and $pp/\overline{p}p$ Data

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(Dated: June 23, 2005)

The PHOBOS experiment at RHIC has measured the total multiplicity of primary charged particles as a function of collision centrality in Au+Au collisions at $\sqrt{s_{NN}} = 19.6$, 130 and 200 GeV. Above $\sqrt{s} \approx 20$ GeV, the total multiplicity per participating nucleon pair ($\langle N_{ch}\rangle/\langle N_{part}/2\rangle$) in central events scales with $\sqrt{s}$ in the same way as $\langle N_{ch}\rangle$ in e^+e^- data. This is suggestive of a universal mechanism of particle production in strongly-interacting systems, controlled mainly by the amount of energy available for particle production (per participant pair for heavy ion collisions). The same effect has been observed in $pp/\overline{p}p$ data after correcting for the energy taken away by leading particles. An approximate independence of $\langle N_{ch}\rangle/\langle N_{part}/2\rangle$ on the number of participating nucleons is also observed, reminiscent of "wounded nucleon" scaling ($N_{ch} \propto N_{part}$), but with the constant of proportionality set by the multiplicity measured in e^+e^- data rather than by $pp/\overline{p}p$ data.

PACS numbers: 25.75.Dw

Central collisions of two gold nuclei at the top energy of the Relativistic Heavy Ion Collider (RHIC) at Brookhaven National Laboratory produce thousands of charged particles. These are the largest particle multiplicities generated in man-made subatomic reactions. The hope is that these complex systems may reveal evidence of the creation and decay of a Quark-Gluon Plasma (QGP), where quarks and gluons are allowed to explore a volume larger than that of a typical hadron.

The high multiplicities in heavy ion collisions typically arise from the large number of nucleon-nucleon collisions which occur, with many of the nucleons struck several times as they pass through the oncoming nucleus. Studies of proton-nucleus collisions demonstrated that the total multiplicity (N_{ch}) does not scale proportionally to the number of binary collisions (N_{coll}) in the reaction, but rather was found to scale more closely with the number of "wounded nucleons" which participate inelastically (N_{part}) [1, 2]. For example, the number of participants is $N_{part} = 2$ for a proton-proton collision and $N_{part} = (N_{coll} + 1)$ for a proton-nucleus collision. Thus, by scaling the particle yields measured in heavy ion collisions by $N_{part}/2$, data from heavy ion collisions may be directly compared with similar yields in elementary pp, $\overline{p}p$ or even the annihilation of e^+e^- into hadrons.

While both e^+e^- and $pp/\overline{p}p$ collisions must ultimately allow a description based on Quantum Chromodynamics (QCD), the theory of the strong interaction, the evolution of these two systems tends to be understood in different ways. The large momentum transfer to the outgoing produced quark and anti-quark in e^+e^- reactions allows the use of perturbative QCD (pQCD) to describe the spectrum of quarks and gluons radiated as the system fragments [3]. Minimum bias collisions of hadrons are not generally thought to be amenable to such a perturbative description, since the transverse momentum exchanges involved are typically less than 1 GeV/c. Instead, phenomenological approaches (e.g. PYTHIA [4]) are used to describe most of the (predominantly soft) particles produced in high energy pp or $\overline{p}p$ collisions.

A basic connection between perturbative and non-perturbative physics has been elucidated by simultaneous measurements of the multiplicity of charged particles and the high-momentum "leading" protons in pp collisions at

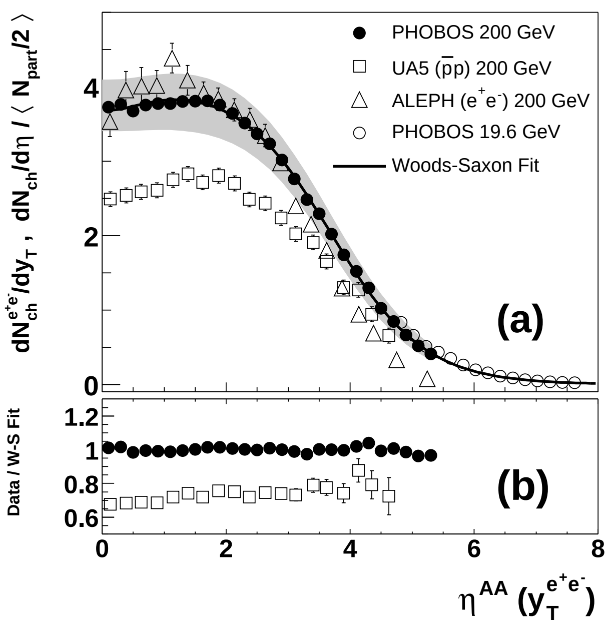

FIG. 1: (a) $dN_{ch}/d\eta/\langle N_{part}/2\rangle$ of charged particles produced in central Au+Au collisions at $\sqrt{s_{NN}} = 200$ and 19.6 GeV (shifted by $\Delta\eta = 2.32$), compared with elementary systems. A Woods-Saxon fit to the 200 GeV Au+Au data is shown. The e^+e^- data are plotted as a function of y_T, the rapidity relative to the thrust axis. (b) PHOBOS and UA5 data divided by a Woods-Saxon fit to the 200 GeV Au+Au data.

the ISR. Basile *et al.* [5] found that the average multiplicity $\langle N_{ch}\rangle$ in pp collisions is similar to that for e^+e^- collisions with $\sqrt{s}_{e^+e^-} = \sqrt{s_{\rm eff}}$, where $\sqrt{s_{\rm eff}}$ is the pp center-of-mass energy minus the energy of the leading particles. This is interpreted as a universal mechanism of particle production controlled dominantly by the available center of mass energy [5].

In this Letter, we report results from the PHOBOS experiment on the total multiplicity of primary charged particles $\langle N_{ch}\rangle$ as a function of N_{part} for heavy ion collisions at $\sqrt{s_{NN}} = 19.6$, 130 and 200 GeV, where $\sqrt{s_{NN}}$ is the nucleon-nucleon center-of-mass energy. Comparisons with $pp/\overline{p}p$ and e^+e^- data are made to investigate whether this universal mechanism of particle production applies in the context of heavy ion collisions.

The PHOBOS multiplicity detector consists of two arrays of silicon detectors which cover nearly the full solid angle for collision events. The "Octagon" detector surrounds the interaction region with a roughly cylindrical geometry covering $|\eta| < 3.2$. Two sets of three "Ring" detectors are placed far forward and backward of the interaction point and surround the beam pipe, covering $3 < |\eta| < 5.4$. The methods used for measuring the multiplicity of charged particles as well as for extracting $\langle N_{part}\rangle$ have been described in more detail in Refs. [6, 7].

Using the data presented in Ref. [7], Fig. 1a shows $dN_{ch}/d\eta/\langle N_{part}\rangle/2$ averaged over the forward and backward hemispheres for the most central Au+Au events at $\sqrt{s_{NN}} = 200$ GeV. The systematic errors (representing a 90% CL interval) depend on η and are shown on the figure as a shaded band. The Au+Au data are compared with $dN_{ch}/d\eta$ for non-single diffractive (NSD) $\overline{p}p$ collisions [8] and dN/dy_T for e^+e^- collisions (with cuts applied to reject large initial-state photon radiation) [9] at $\sqrt{s} = 200$ GeV. The variable y_T is the rapidity of charged particles relative to the event thrust axis, assuming all particles to have the pion mass.

It is observed that the Au+Au data are very similar in magnitude and shape to the e^+e^- data at the same $\sqrt{s}$, and similar in shape to the $\overline{p}p$ data (as shown in Fig. 1b), over a large range in η. The differences between the e^+e^- and Au+Au distributions shown in Fig. 1a can be partly attributed to the different kinematic variables. JETSET calculations indicate that the y_T distribution is slightly narrower than the corresponding pseudorapidity distribution in e^+e^- collisions, with a higher plateau height. Yet, even without taking this into account, the difference between the distributions is no more than $\pm10\%$ for $|\eta|$ and $|y_T| < 4$ [4]. However, the same calculations also show that the choice in kinematic variables does not explain the difference in the forward region (above $|\eta| = 4$), although this may not be surprising, as this region should show some residual effect of the presence of the spectator nucleons.

The similarity of the angular distributions indicates that the total yield of charged particles in e^+e^- and central Au+Au collisions should also be similar for the same $\sqrt{s}$, when the nuclear data are scaled by the number of participant pairs. To correct for the small acceptance losses in the PHOBOS apparatus (which covers $|\eta| < 5.4$), we have used several methods inspired by the excellent agreement of the lowest energy PHOBOS data with the higher energy data when shown as a function of $\eta' = \eta - y_{beam}$ [7]. PHOBOS data from $\sqrt{s_{NN}} = 19.6$ GeV for $\eta > 2.5$, shifted by $\Delta\eta = y_{200} - y_{19.6} = 2.32$ (the difference in beam rapidities between the two energies), displays the limiting behavior discussed in Ref. [7]. This effectively extends the rapidity coverage to $\eta \sim 8$. A Woods-Saxon function for dN/dy fit to the Au+Au data, also provides a reasonable description of the $dN/d\eta$ distribution, and extrapolates through the lower energy data as well. Thus, in one method, we integrate $dN_{ch}/d\eta$ for $\sqrt{s_{NN}} = 130$ and 200 GeV for $\eta' < 0$ and then use the PHOBOS data at $\sqrt{s_{NN}} = 19.6$ GeV for $\eta' > 0$. We also integrate Woods-Saxon fits, similar to that shown in Fig. 1a, for $|\eta| < 8$. These two approaches agree within 2% for central events. For the lowest RHIC energy, we simply integrate the charged particles in the PHOBOS acceptance.

In Fig. 2a, data on N_{ch} from pp, $\overline{p}p$, e^+e^- and central heavy ion collisions (scaled by $N_{part}/2$) are shown as a function of $\sqrt{s}$. The pp, $\overline{p}p$, and e^+e^- data and errors are taken from a compilation [10] and no further corrections are applied. The errors shown are the quadratically combined statistical and systematic errors. Heavy ion data are shown for central Au+Au events at RHIC (this work), Au+Au events from E895 at the AGS ($\sqrt{s_{NN}} = 2.6-4.3$ GeV) [11] and Pb+Pb events from NA49 at the SPS ($\sqrt{s_{NN}}$ = 8.6, 12.2 and 17.3 GeV) [12]. A PHOBOS Au+Au data point at $\sqrt{s_{NN}} = 56$ GeV has been added by using the measured value at midrapidity [13] and using the universal limiting distribution described in Ref. [7] to approximate the shape of the full distribution. All of the errors shown for the heavy ion data are systematic.

Perturbative QCD calculations are able to predict the dependence of the total multiplicity in e^+e^- collisions as a function of $\sqrt{s}$, $N_{e^+e^-}(s) = C\alpha_s(s)^A \exp(\sqrt{B/\alpha_s(s)})$, with A and B fully calculable within pQCD[14]. The QCD scale Λ_{QCD} is set to 225 MeV, leaving only a constant of proportionality C free to fit to the experimental data. A fit to the e^+e^- data has been made with this expression ("e^+e^- fit") and has been used in Fig. 2b to see how the various systems compare with e^+e^- data by scaling all of the data at a given $\sqrt{s}$ by this function.

Fig. 2b shows that the $pp/\overline{p}p$ data are about 30% below e^+e^- over the full range of energies. However, rescaling the $\sqrt{s}$ of each point by a factor of 1/2, $\sqrt{s_{\rm eff}} = \sqrt{s}/2$, brings the data into reasonable agreement with the e^+e^- trend, as shown by the open diamonds. This is consistent with measurements of leading protons in pp collisions, which find dN/dx_F (where $x_F = 2p_z/\sqrt{s}$ in the collider reference frame) to be approximately constant for non-diffractive events over a large range of $\sqrt{s}$ [15] and thus $\langle x_F \rangle \sim 1/2$.

Unlike the $pp/\overline{p}p$ data, the heavy ion data does not follow the e^+e^- trend over the whole energy range. Instead, they lie below the pp data at AGS energies, crosses through the pp data between AGS and SPS energies, and joins smoothly with the e^+e^- data above the top SPS energy. Thus, at high energies, the multiplicity measured per participant pair in Au+Au collisions scales in a similar way to e^+e^- data at the *same* $\sqrt{s}$. If we understand the lower effective $\sqrt{s}$ in pp collisions as stemming from the "leading particle effect", where the leading proton carries off a substantial amount of the available energy, the Au+Au data suggest a substantially reduced leading particle effect in central collisions of heavy nuclei at high energy.

The alleviation of the leading particle effect might not be so surprising in central nuclear collisions. In the Glauber model, each participating nucleon is typically struck $4-6$ times on average as it passes through the oncoming gold nucleus in a central event (the exact value of $\overline{\nu}$ depending on the energy-dependent nucleon-nucleon inelastic cross section, $\sigma_{NN}(s)$). One could speculate that the multiple collisions simultaneously excite and dissociate the participating nucleons, transferring much

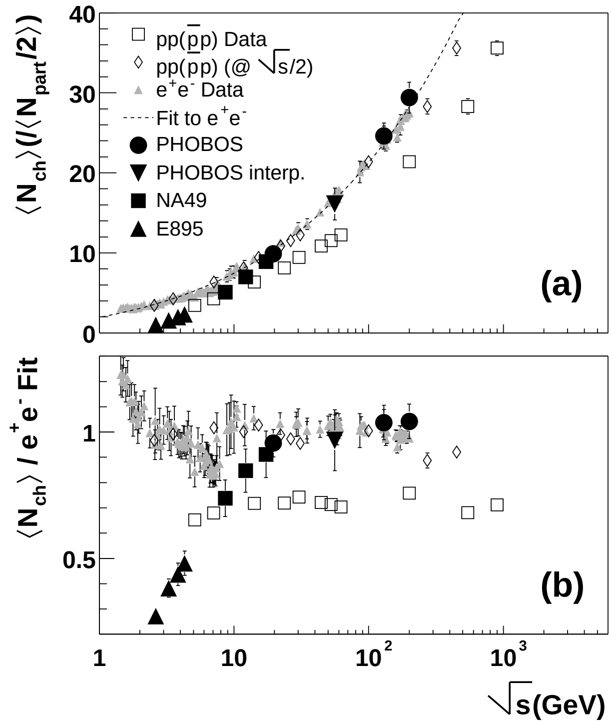

FIG. 2: (a) The total charged multiplicity $\langle N_{ch} \rangle$ for pp, $\overline{p}p$, e^+e^- and central Au+Au events as a function of $\sqrt{s}$. The Au+Au data are normalized by $N_{part}/2$. The dotted line is a perturbative QCD expression fit to the e^+e^- data. The diamonds are the $pp/\overline{p}p$ data with $\sqrt{s_{\rm eff}} = \sqrt{s}/2$. (b) The data in (a) divided by the e^+e^- fit, to allow direct comparison of different data at the same $\sqrt{s}$.

more of the energy from the forward direction towards midrapidity than found in an average $pp/\overline{p}p$ collision - but ultimately limited by the total incident energy. This hypothesis should be testable in proton-nucleus collisions, by measuring particle yields as a function of ν as was done in Refs. [16, 17]. The data in those references suggest that pion yields, whether in the projectile region ($y > 0$) [17] or integrated over 4π [16] increase rapidly for $\nu < 3$ and then much more slowly for $\nu > 3$. However, limited experimental acceptances and theoretical uncertainties preclude making any strong conclusions regarding the relationship between the energy loss of the projectile and the total charged multiplicity.

In Fig. 3 $\langle N_{ch} \rangle / \langle N_{part}/2 \rangle$ is shown for PHOBOS data at three RHIC energies as a function of N_{part}. The 90% CL systematic error on the centrality dependence of $\langle N_{ch} \rangle / \langle N_{part}/2 \rangle$ is shown as a shaded band, and represents a combination of several factors, dominated by the uncertainty of the extrapolation procedure to extract N_{ch} over the full solid angle.

It might have been expected that, in events with larger impact parameters, each participant would have fewer collisions on average and thus not be fully dissociated. However, within the systematic errors, the total yield per participant pair is approximately constant (within 10%) over the measured centrality range, $65 < \langle N_{part} \rangle < 358$, which corresponds to $3 < \overline{\nu} < 6$, where $\overline{\nu}$ is the average number of collisions undergone by each oncoming nucleon. Thus, it appears that only the first few collisions have any appreciable effect on particle production. It should be noted that this simple scaling is not observed for particle yields measured in a limited pseudorapidity range near midrapidity [6].

Proton-antiproton data exist at 200 GeV, but not for the other two RHIC energies. We use a parametrization of *pp* data from Ref. [18], $\langle N_{ch} \rangle = -4.2 + 4.69 s^{.155}$, for 19.6 and 130 GeV. Several measurements exist in e^+e^- at 200 GeV, but not for the other two energies. For these we use the pQCD formula for $N_{e^+e^-}$, the quality of the fit clearly indicated in Fig. 2b. Fig. 3 shows that the Au+Au data are consistent with "wounded nucleon" scaling, in that the multiplicity is proportional to N_{part} ($N_{ch} \propto N_{part}$). However, N_{ch} clearly does *not* scale simply with the multiplicity measured in *pp* collisions at the same energy. Rather, for a large range of impact parameter, the multiplicity scales approximately with the total multiplicity in e^+e^- annihilation at the same $\sqrt{s}$. Thus, it appears that the first few collisions per participant are sufficient to liberate as much energy for particle production as an e^+e^- reaction.

However, the rapid approach of $\langle N_{ch} \rangle / \langle N_{part}/2 \rangle$ in central heavy ion collisions below $\sqrt{s_{NN}} \sim 20$ GeV towards the e^+e^- data complicates any simple geometric interpretation, as all of the heavy ion data compared are for a similar range of impact parameters. One feature that might point to why the particle yields at the AGS and SPS are perhaps "suppressed" relative to e^+e^- data (and even to *pp* data at lower energies, as noted in Ref. [12]) is the magnitude of the ratio of net baryons to pions in the system. This ratio, which scales approximately as N_{part}/N_{ch}, is $O(50\%)$ at AGS energies [11], but is $O(1\%)$ at RHIC [19]. In a thermal statistical approach [20], this reflects the decrease of the baryon chemical potential with increasing beam energy.

In conclusion, the PHOBOS experiment has measured the normalized charged-particle multiplicity $\langle N_{ch} \rangle / \langle N_{part}/2 \rangle$ in Au+Au collisions at three RHIC energies as a function of the centrality of the collision. Above CERN SPS energies, the total multiplicity per participating nucleon pair, $\langle N_{ch} \rangle / \langle N_{part}/2 \rangle$, in central events scales with $\sqrt{s}$ in the same way as e^+e^- data. This is suggestive of a universal mechanism of particle production in strongly-interacting systems, controlled mainly by the amount of energy available for particle production. This may be related to the multiple collisions suffered by each participant nucleon, which could substantially reduce the leading particle effect seen previously in *pp* collisions. The weak centrality dependence for $\langle N_{ch} \rangle / \langle N_{part}/2 \rangle$, reminiscent of "wounded nucleon" scaling, suggests that after the first few collisions per participant, the multiplicity per participant pair saturates near the value measured in e^+e^- reactions. Ultimately, the existence of simple scaling behavior with $\sqrt{s_{\rm eff}}$ and N_{part} indicates stronger constraints on particle production than previously considered theoretically. Thus, these results may provide a new perspective on particle production in heavy ion collisions.

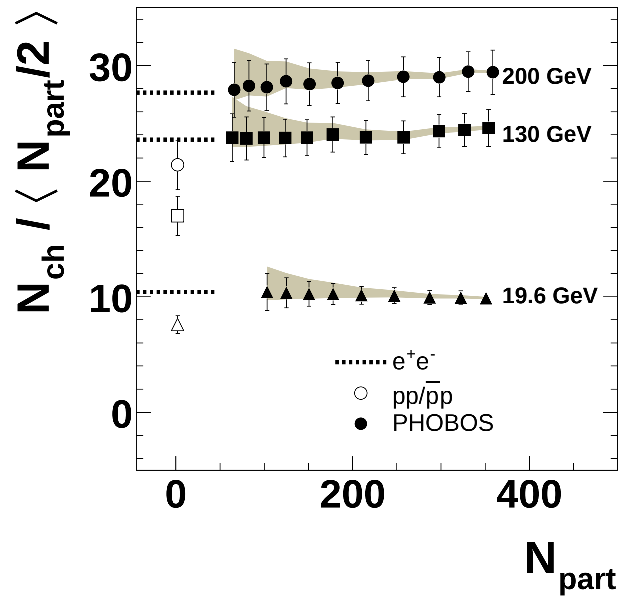

FIG. 3: $\langle N_{ch} \rangle / \langle N_{part}/2 \rangle$ is shown vs. N_{part} for $\sqrt{s_{NN}} =$ 19.6, 130, and 200 GeV as closed symbols. The error includes contributions from the uncertainty on overall N_{ch} scale and N_{part} scale. The shaded band shows the uncertainty on the extrapolation procedure. The open symbols show UA5 data at 200 GeV and results from an interpolation for the lower energies. The dotted lines show the values from the e^+e^- fit.

This work was partially supported by U.S. DOE grants DE-AC02-98CH10886, DE-FG02-93ER40802, DE-FC02-94ER40818, DE-FG02-94ER40865, DE-FG02-99ER41099, and W-31-109-ENG-38 as well as NSF grants 9603486, 9722606 and 0072204. The Polish groups were partially supported by KBN grant 2 PO3B 103 23. The NCU group was partially supported by NSC of Taiwan under contract NSC 89-2112-M-008-024.

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